# CHAPTER 2: FACTORS AFFECTING SLOPE FAILURE

## 2.1 Introduction

Slope failure occurs when the downward movements of material due to gravity and shear stresses exceeds the shear strength. Therefore, factors that tend to increase the shear stresses or decrease the shear strength increase the chances of failure of a slope. Different processes can lead to reduction in the shear strengths of rock mass. Increased pore pressure, cracking, swelling, decomposition of clayey rock fills, creep under sustained loads, leaching, strain softening, weathering and cyclic loading are common factors that decrease the shear strength of rock mass. In contract to this the shear stress in rock mass may increase due to additional loads at the top of the slope and increase in water pressure in cracks at the top of the slope, increase in soil weight due to increased water content, excavation at the bottom of the slope and seismic effects. In addition to these reasons factor contributing in failure of slope are properties of rock mass, (slope geometry), state of stress, temperature and erosion. The factors affecting in slope failure have been shown in Table 2.1 and important factors have been described in this chapter.

| Sr. No | Name of the parameters and properties | Details |
|---|---|---|
| 1 | Geological Discontinuities | Fault, Joint, bedding plane, |
| 2 | Water | Ground water, drainage pattern, rainfall, permeability, aquifer |
| 3 | Strength | Shear strength, compressive strength, tensile strength |
| 4 | Geotechnical parameters | Gran size, moisture content, atterberg limit, etc. |
| 5 | Method of construction | Shovel, dumper, BWE or combination |
| 6 | Dynamic forces | Blasting, Seismic activity |
| 7 | Geometry of slope | Height and angle of slope, bench height and angle, |

## 2.2 Geological discontinuities

The stability of rock slopes is significantly influenced by the structural discontinuity in the rock in which the slope is excavated. A discontinuity is a plane or surface that marks a change in physical or chemical characteristics in a soil or rock mass. A discontinuity can be in the form of a bedding plane, schistosity, foliation, joint, cleavage, fracture, fissure, crack, or fault plane. This discontinuity controls the type of failure which may occur in a rock slope. The properties of discontinuities such as orientation, persistence, roughness and infilling are play important role in the stability of jointed rock slope. Discontinuities may occur multiple times with broadly the same mechanical characteristics in a discontinuity set, or may be a single discontinuity. It makes a soil or rock mass anisotropic.

The orientation of a major geological discontinuity relative to an engineering structure also controls the possibility of unstable conditions. The mutual orientation of discontinuities determines the shape of the individual blocks. Orientation of a discontinuity can be defined by its dip (maximum inclination to the horizontal) and dip direction (direction of the horizontal trace of the line of dip, measured clockwise from north). The strike is at right angles to the dip direction, and the relationship between the strike and the dip direction is illustrated in Figure 1. Figure 2a explain the possibility if plane failure at lower value of dip angle with respect of slope angle however, as the dip angle of discontinuity increase and become sub parallel to the slope angle the slope become relatively stable (figure 2b). However further increase in dip angle in discontinuity make is liable to undergo toppling failure (figure 2c).
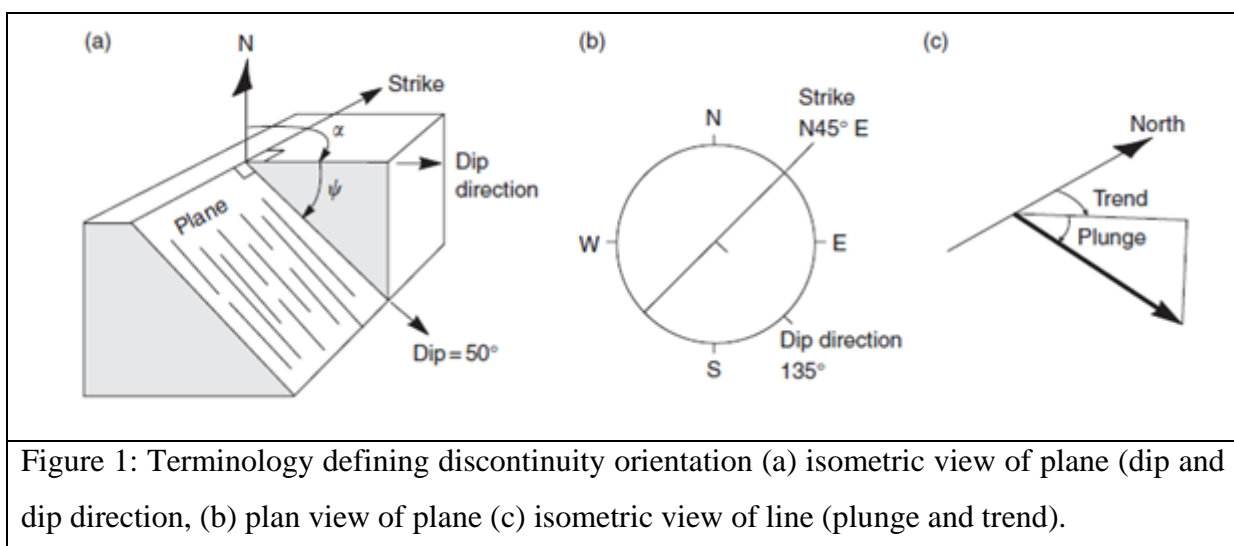


Figure 1: Terminology defining discontinuity orientation (a) isometric view of plane (dip and dip direction, (b) plan view of plane (c) isometric view of line (plunge and trend).
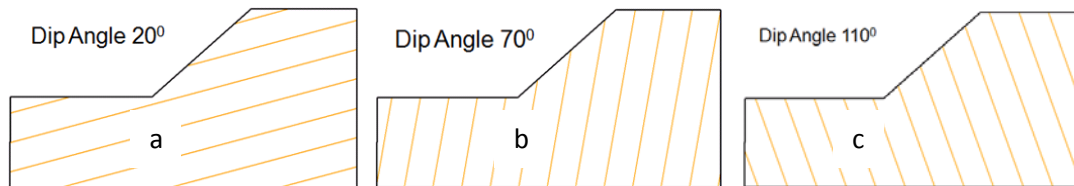
Figure (2a-c) illustrates the effect of discontinuity orientation on the types of slope failure

A Jointed rock exhibits a higher permeability and, reduced shear strength along the planes of discontinuity apart from increased deformability and negligible tensile strength in directions normal to those planes. The degree of fracturing of a rock mass is controlled by the number of joint in a given direction. A rock mass containing more joints is also considered as more fractured. The spacing of adjacent joints largely controls the size of individual blocks controlling the mode of failure. A close spacing of joints gives low cohesion of rock mass and responsible for circular or even flow failure. It also influences the rock mass permeability.

Persistence of discontinuities defines, together with spacing, the size of blocks that can slide from the face (figure 3). Furthermore, a small area of intact rock between low persistence discontinuities can have a positive influence on stability because the strength of the rock will often be much higher than the shear stress acting in the slope.

Roughness of joint surface is a measure of the inherent unevenness and waviness of the surface of discontinuity relative to its mean plane. The friction angle of a rough surface comprises two components the friction of the rock material ($\varphi$), and interlocking produced by the irregularities of the surface (i).
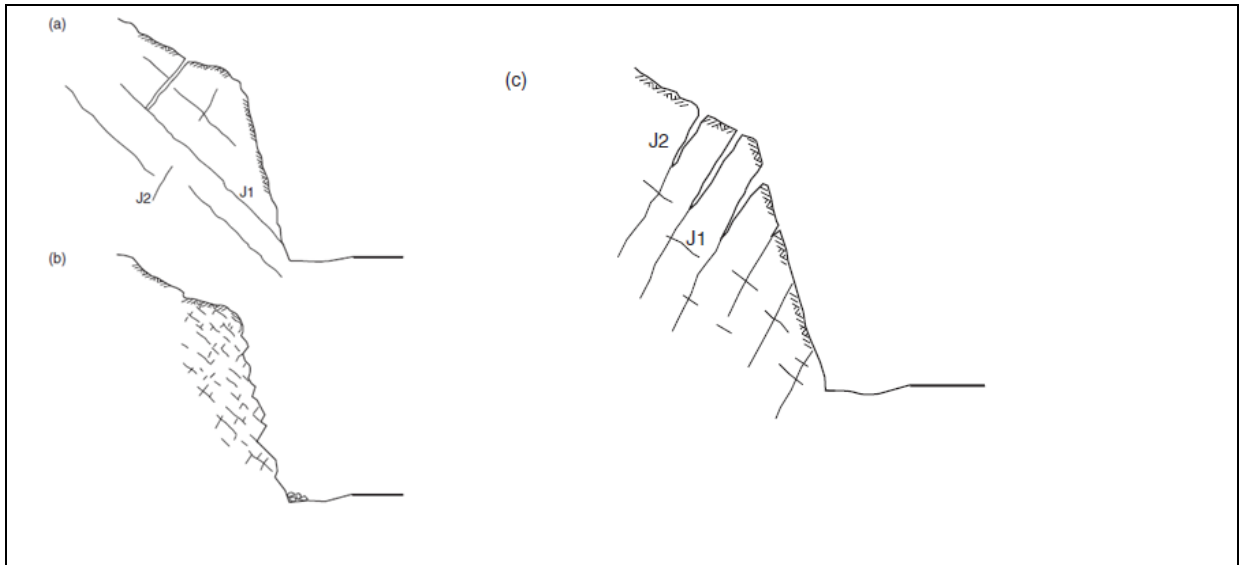
Figure 3: Effects of persistence on slope stability

## 2.3  Effect of Water

The effect of water on the slope can be considered into two fold. One is ground water or aquifer below the surface that generates porewater pressure and the other is rainwater infiltration that seeps through surface and flows along the slope generating water pressure. It is related to the surrounding precipitation levels, topography, nearby water masses, and the geo-hydrological characteristics of the rock mass (Sjöberg, 1999).

In medium to hard rock, water occupying the fractures within the rock mass can significantly reduce the stability of a rock slope. Water pressure acting within a discontinuity reduces the effective normal stress acting on the plane, thus reducing the shear strength along that plane. If a load is applied at the top of a slope, the pore pressure increases. Such a load can lead to immediate failure of the slope if it exceeds its shear strength of slope. Water filling in discontinuities can result in lowering of stability condition for natural or artificial slopes. Figure 4 shows a rock blocking resting on an inclined plane and separated from the upper part of the slope by a sub vertical discontinuity plane. The water applies horizontal and vertical pressure along the discontinuities. The uplift force U is also developed due to water at the surface between the block and its base. The water pressure increases linearly with depth down to the intersection of the sub vertical plane with the base and linearly decreases from the intersection point to the lower edge of the block in contact with the surface where the water pressure is zero (Gaine, 1992).

Addition of water from rainfall and snow melt adds weight to the slope. In addition to it ground water also exists nearly every where beneath the earth surface. Such water fills the pore spaces between the grains or fractures in the rock. Such water can seep into discontinuity present in the rock mass replacing the air in the pore space thus increasing the weight of the soil. It leads to increase in effective stress resulting into failure of the slope. Figure 5 depicts the effect of water content in the rockmass on factor of safety of the slope found on the different slope angles. It depicts for an increase in slope angle from $60^0$ to $80^0$, the factor of safety of the slope under dry rock mass conditions reduces from value of 2 about 1. Whereas, under the saturated rockmass conditions increase in the slope angle makes it unstable when value exceed $70^0$.
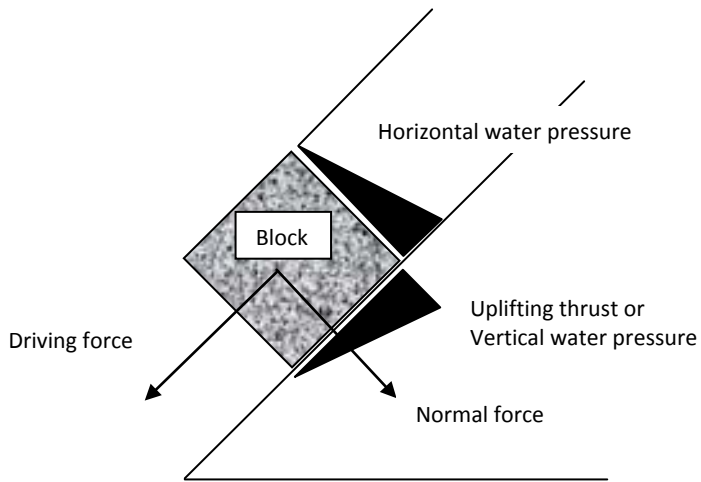
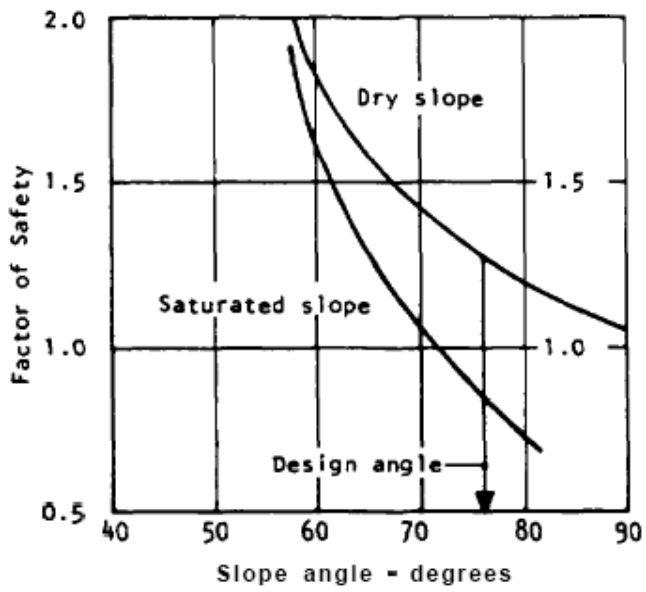Figure 4: Diagram of water pressure acting on a block



Figure 5: Variation in Factor of Safety with slope angle (after Hoek and Bray, 1977)

In soil and mine waste dump in surface mines, if the unconsolidated material is dry or non-saturated, an increase in load compress the air in the pore spaces thus compacting the mass and bringing grains or rock fragments closer together which increase its shear strength. However, when a rock mass is saturated, an increase in external pressure leads to an increase in the pore pressure, as water is relatively incompressible. This increase in pore pressure has a buoying effect, and can be enough to support the weight of the overlying rock mass, thereby reducing friction and the shear strength.

Unconsolidated sediments behave in different ways depending on whether they are dry or wet (Terzaghi, 1943). Dry Unconsolidated grain from a pile with a slope angle control by the angle of repose (figure 6a) which generally varies between $30-37^0$. In contrast to this, a slightly wet unconsolidated material exhibits a very high angle of repose because surface tension between water and the grains tends to hold the grains in their places (figure 6b). This is due to capillary attraction resulting into surface tension which holds the wet material together as a cohesive mass. However, when the material is saturated with water the angle of repose reduces substantially (figure 6c). This is because the water gets in between the grains eliminating grain to grain frictional contacts.
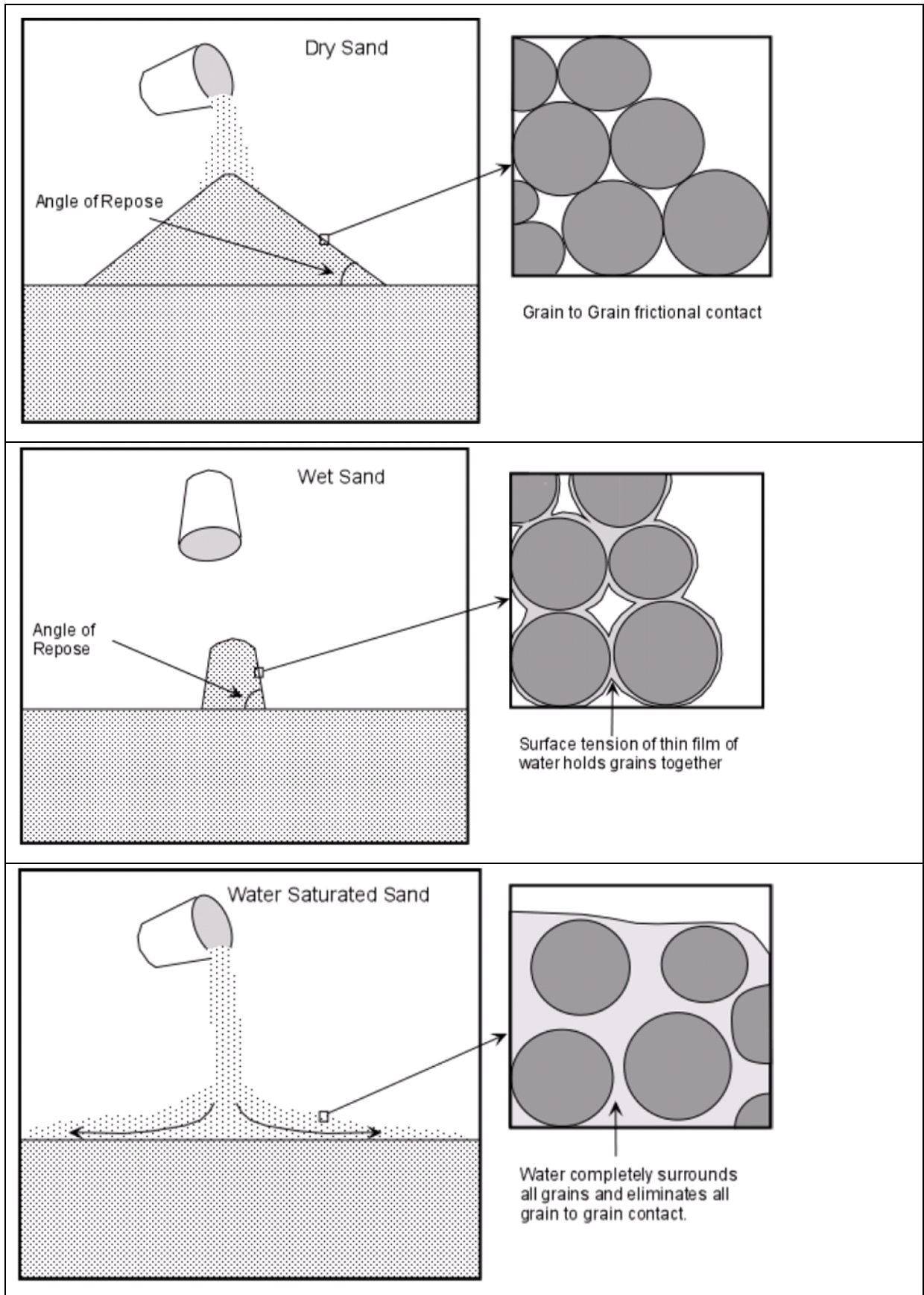
Figure 6: Effect of water content in unconsolidated grain of piles.

## 2.4 Geotechnical Properties of Material

The important geotechnical properties affecting stability of a slope are shear strength of material, particle size distribution, density, permeability, moisture content, plasticity and angle of repose. The strength of rockmass is a very important factor that affects the stability of slopes. It is a function of strain rate, drainage condition during shear, effective stresses acting on the soil prior to shear, the stress history of the soil, stress path, and any changes in water content and density that may occur over time. It consists of cohesion and friction angle of material. Friction is a resisting force between two surfaces. Cohesion results from a bonding between the surfaces of particles. It is dependent upon many factors, including material properties, magnitude and direction of the applied force and the rate of application, drainage conditions in the mass, and the magnitude of the confining pressure.

The relationship between the peak shear strength $\tau$ and the normal stress $\sigma$ can be represented by the Mohr-Coulomb equation (figure 7):

$$\tau = c + \sigma tan\phi$$

where c is the cohesive strength and $\phi$ is the angle of friction.
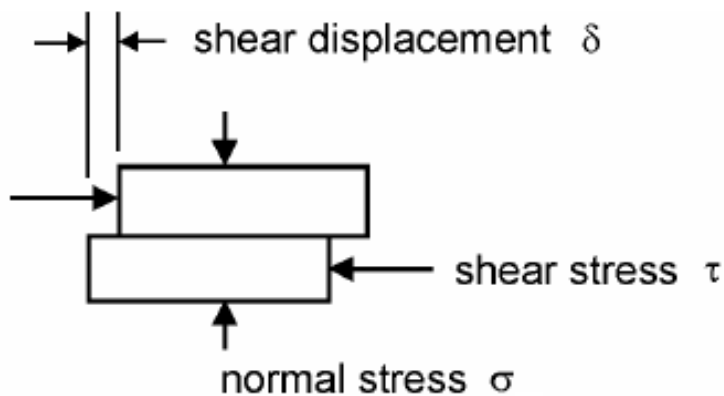


**Figure 7: Shear testing of discontinuities or between two plane**

The shear strength of Patton's saw-tooth specimens (figure 8) can be represented by:

$$\tau = \sigma tan\,(\phi + i)$$

where $\phi$ is the basic friction angle of the surface and $i$ is the angle of the saw-tooth face.
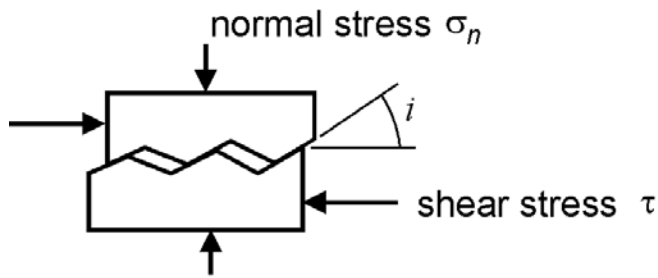
Figure 8: Patton's experiment on the shear strength of saw-tooth specimens.

Materials that are coarse or have a rough texture have greater opposing frictional forces or shear strength to resist the movement. However, unconsolidated materials such as sediment and soil that have no strong cementing material or interlocking crystal structure is far less stable than hard rock. Rate of loading, degree of compaction and moisture content of the rockmass also affect its slope stability.

Density is also important factor in slope stability. However, its effect is more in mine waste dumps where it is a function of the manner of deposition, gradation, and loading history. A relatively small increase in density can increase the shear strength of waste dump, but it also increases the stresses due to gravity loading.

Permeability of the soil or waste material affects seepage pattern and water levels in the slope. This, in turn, can affects shear resistance of the material depending on the size and shapes of the particles, degree of compaction and the gradation of soil and its density (Campbell, 1975 and Aubeny and Lytton, 2004).

Angle of repose of loose material is influenced by the size and shape of its particles. Smooth, rounded particles have a lower angle of repose than rough, angular particles. Coarse fragments can maintain a greater slope than fine fragments.

## 2.5 Mining Methods

Factor related to method of mining and affecting stability of slope include method used for preparation of foundation, method of stripping, placement and rehandling of dump material. Important factors with regard to dump configuration, zonation, potential failure surface, engineering properties of dump material and pore water pressure are also very significant. The density of the waste dump is also controlled by the manner of deposition gradation and loading history. This in turn can affect the shear strength of waste dump. Further the type of equipment used for dumping of over burden also affects its compaction. A combination of shovel and dumper along with the use of bulldozers for leveling creates a waste dump of maximum compaction, which gives maximum strength of dump materials. In contrast to it, the bucket wheel excavator alone or in conjunction with spreaders places the material of low strength in a very loose state. The dragline places the spoil dump material in dumps from height and thus, causes some compaction to take place. Therefore, the material in dragline waste dumps show densities in between the above two categories.

## 2.6 State of stress

In some locations, high in-situ stresses may be present within the rock mass. High horizontal stresses acting roughly perpendicular to a cut slope may cause blocks to move outward due to the stress relief provided by the cut. High horizontal stresses may also cause spalling of the surface of a cut slope. The stored stresses is most likely be relieved to some degree near the ground surface or perpendicular to slope walls.

## 2.7 Geometry slope:

Important parameters of slope geometry affecting its stability include height and angle of slope. The critical height of slope depends on shear strength, density and bearing capacity of the slope foundation. Slope stability generally decreases with increase in height of slope. As the slope height increases, the shear stress within toe of slope increases due to added weight. Shear stress is also related to the mass of the material and the slope angle. With increasing slope angle, the tangential stress increases which result in increase in shear stress thus reducing its stability (figure 9).



Figure 9 : Effect of slope angle on slope stability
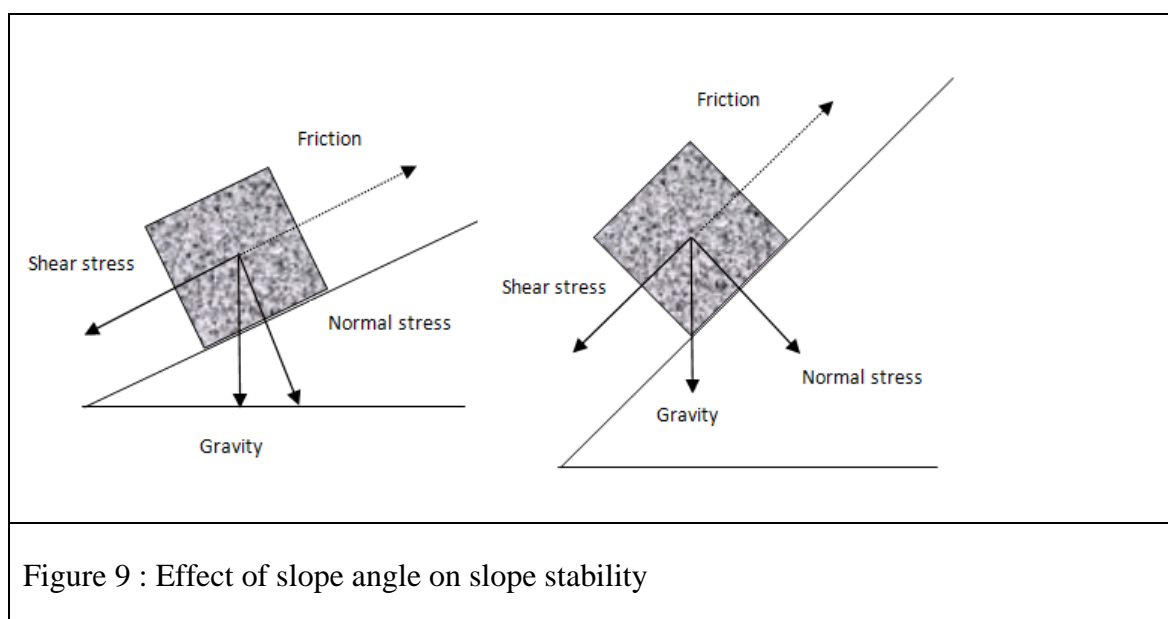
### 2.8 Temperature

The effects of temperature also influence the performance of a rock slope. Large temperature changes can cause rock to spall due to the accompanying contraction and expansion. Freezing of water in discontinuities causes more significant damage by loosening the rock mass. Repeated freeze cycles may result in gradual loss of strength. Except for periodic maintenance requirements, such effects are a surface phenomenon and are most likely of little concern for permanent slopes. However, in a few cases, surface deterioration could trigger slope instability on a larger scale.

### 2.9 Erosion

Two aspects of erosion need to be considered from slope stability point of view. The first is a large scale erosion, such as a river erosion occurring at the base of a slope. The second is a relatively localized erosion caused by groundwater or surface runoff. In the first type, erosion changes the geometry of the potentially unstable rock mass. The removal of material at the toe of a potential slide reduces the confining stress that may be stabilizing the slope. Localized erosion of joint filling material, or zones of weathered rock, can effectively decrease interlocking between adjacent rock blocks. Loss of such interlocking significantly reduces the rock mass shear strength. The resulting decrease in shear strength may allow a previously stable rock mass to move causing slope failure. In addition, localized erosion may also result in increased permeability and ground-water flow thus affecting the stability of rock slope.

### 2.10 Seismic effect

Seismic waves passing through rock adds stress which could causes fracturing in the rock mass. As a result, friction is reduced in unconsolidated masses as they are tarred apart which may induce liquefaction. Landslide is one of the major hazards resulting due to earthquakes. Blasting and earthquakes events affect rock slopes in two distinct ways with different time scales. The first effect is in the form of immediate co-seismic detachment of rock from a slope face. The second effect occurs over a longer timeframe involving opening of fissures and rock fracturing that may result in rock dislodgements in the future. Such effects of seismicity on rock slopes strongly depend on local conditions of the rock mass. Geological and topographic set up of the area may also control the level of susceptibility of failure of rock slope under the influence of seismicity.

## 2.11 Vegetation

Plant roots provide a strong interlocking network to hold unconsolidated materials together and prevent flow. Furthermore, plants are very effective in removing water from the soil, thus increasing the shear strength. Although, the extra weight of plants may cause a slight destabilizing effect if the root network is of limited extent, the overall vegetation increases stability of a slope. Different types of vegetation like grasses, herbs, shrubs and trees are used to stabilize the slope stability and reinforcement of the soil (Coppin and Richards, 1990) (figure 10). Grasses are quick to establish, versatile and cheap and have wide range of tolerance, with dense cover but shallow rooting requiring regular maintenance. Herbs have deeper rooting, nitrogen fixers, compatible with grasses but they have expensive seed, difficult establishment and winter dieback. Shrubs have deeper rooting and robust and cheap requiring low maintenance. It offers substantial ground cover and available in many ever green species. Trees have substantial rooting, low maintenance but require long time to establish and are slow growing. The relative effectiveness of these different vegetation patterns in a specific locale is a function of quality of vegetation, topography, slope, hydrology, geology, and soils characteristics. The loss or removal of slope vegetation can result in either increased rates of erosion or higher frequencies of slope failure.
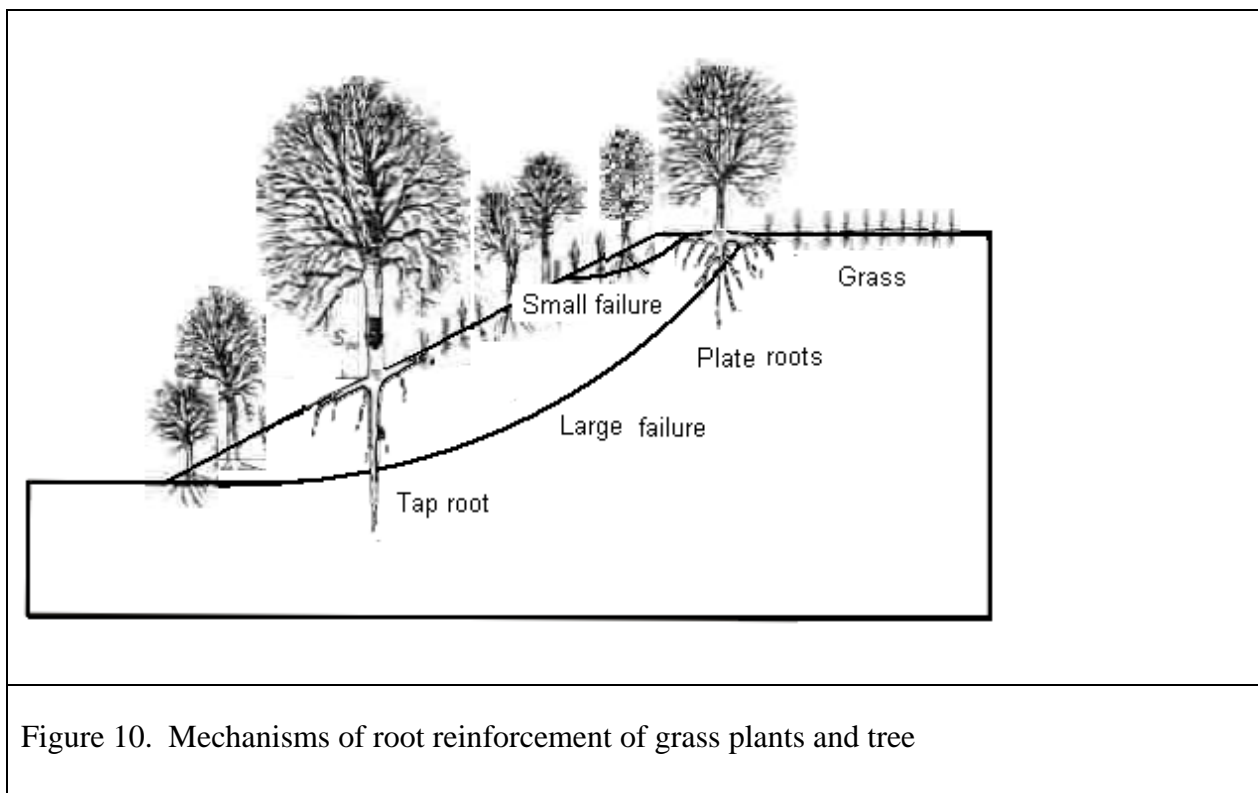


Figure 10.  Mechanisms of root reinforcement of grass plants and tree